

JOINT INVENTORS

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# **APPLICATION FOR UNITED STATES LETTERS PATENT**

## **S P E C I F I C A T I O N**

TO ALL WHOM IT MAY CONCERN:

Be it known that we, Jeremy H. BURROUGHES, a citizen of Great Britain, residing at 36 Rustat Road, Cambridge CB1 3QT, United Kingdom; Julian C. CARTER, a citizen of Great Britain, residing at 6 High Street, Dry Drayton, Cambridge CB3 8BS, United Kingdom; Alec G. GUNNER, a citizen of Great Britain, residing at The School House, Haverhill Road, Horseheath, Cambridgeshire CB1 6QR, United Kingdom; Stephen K. HEEKS, a citizen of Great Britain, residing at 127 Rampton Road, Cottenham, Cambridge CB4 4JJ, United Kingdom; and Ian S. MILLARD, a citizen of Great Britain, residing at 69A Histon Road, Cambridge CB4 3JD, United Kingdom, have invented new and useful OPTO-ELECTRICAL DEVICES, of which the following is a specification.

## OPTO-ELECTRICAL DEVICES

This invention relates to opto-electrical devices, for example devices for emitting or detecting light.

One specific class of opto-electrical devices is those that use an organic material for light emission or detection. Light-emissive organic materials are described in PCT/WO90/13148 and US 4,539,507, the contents of both of which are incorporated herein by reference. The basic structure of these devices is a light-emissive organic layer, for instance a film of a poly(p-phenylenevinylene ("PPV"), sandwiched between two electrodes. One of the electrodes (the cathode) injects negative charge carriers (electrons) and the other electrode (the anode) injects positive charge carriers (holes). The electrons and holes combine in the organic layer generating photons. In PCT/WO90/13148 the organic light-emissive material is a polymer. In US 4,539,507 the organic light-emissive material is of the class known as small molecule materials, such as (8-hydroxyquinoline)aluminium ("Alq3"). In a practical device one of the electrodes is typically transparent, to allow the photons to escape the device.

Figure 1 shows a typical cross-sectional structure of such an organic light-emissive device ("OLED"). The OLED is typically fabricated on a glass or plastic substrate 1 coated with a transparent material such as indium-tin-oxide ("ITO") to form an anode 2. Such coated substrates are commercially available. The ITO-coated substrate is covered with at least a thin film of an electroluminescent organic material 3 and a final cathode layer 4, which is typically a metal or alloy.

Some particularly attractive applications of such devices are as displays in battery-powered units such as portable computers and mobile phones. Therefore, to extend the battery life of such units, there is a particularly strong need to increase the efficiency of the light-emissive devices. One route to improving efficiency is by careful choice and design of the light-emissive material itself. Another is by

optimising the physical layout of the display. A third is by improving the conditions for charge injection into and charge recombination in the emissive layer.

To improve the conditions for charge injection into and charge recombination in the emissive layer it is known to include a charge transport layer of an organic material such as polystyrene sulphonic acid doped polyethylene dioxythiophene ("PEDOT-PSS") between one or both of the electrodes and the emissive layer. A suitably chosen charge transport layer can enhance charge injection into the emissive layer and resist reverse flow of charge carriers, which favours charge recombination. It is also known to form the electrodes from materials having work functions that aid the desired flow of charge carriers. For example, a low work function material such as calcium or lithium is preferred as the cathode. PCT/WO97/08919 discloses a cathode formed of a magnesium:lithium alloy.

According to one aspect of the present invention there is provided an opto-electrical device comprising: an anode electrode; a cathode electrode; and an opto-electrically active region located between the electrodes; the cathode electrode including a first layer comprising a compound of a group 1, group 2 or transition metal; a second layer comprising a material having a work function below 3.5 eV; and a third layer spaced from the opto-electrically active region by the first and second layers and having a work function above 3.5eV.

According to a second aspect of the present invention there is provided a method for forming an opto-electrical device, the method comprising: depositing an anode electrode; depositing over the anode electrode a region of an opto-electrically active material; depositing over the region of opto-electrically active material a layer comprising a compound of a group 1, group 2 or transition metal and a layer comprising a material having a work function below 3.5 eV; and depositing over those layers a material having a work function above 3.5 eV to form a third cathode layer.

The compound is preferably a compound of a group 1 or group 2 metal, especially a compound of a group 1 metal, such as lithium. The compound may, for example, be any of a halide (e.g. a fluoride), an oxide, a carbide or a nitride. Some of these compounds may be electrically conductive, others may be electrically insulative. The compound may be a complex of a group 1, group 2 or transition metal, especially an organic complex.

The first layer may be spaced from the opto-electrically active region by the second layer. Alternatively the second layer may be spaced from the opto-electrically active region by the first layer. The closer of the first and second layers to the opto-electrically active region is preferably adjacent that region or there may be one or more other layers (preferably electrically conductive layers) between the first layer and the opto-electrically active region. The opto-electrically active region is suitably in the form of a layer, preferably a layer of an opto-electrically active material. The opto-electrically active region is suitably active to emit light or to generate an electrical field in response to incident light. The device is preferably an electroluminescent device.

The second layer suitably comprises a metal selected from the group comprising: Li, Ba, Mg, Ca, Ce, Cs, Eu, Rb, K, Y, Sm, Na, Sr, Tb or Yb, or an alloy of two or more of those metals; or an alloy or one or more of those metals with another metal such as Al, Zr, Si, Sb, Sn, Zn, Mn, Ti, Cu, Co, W, Pb, In or Ag.

The thickness of the first layer is suitably between 10 and 150 Å. The thickness of the second layer is suitably less than 1000 Å, and preferably less than 500 Å. The thickness of the second layer is suitably more than 40 Å or 100 Å, and optionally more than 150 Å or 200 Å. The thickness of the second layer is preferably in the range from 40 Å to 500 Å.

The first layer preferably comprises more than 80%, more than 90%, or than 95% or most preferably more than 99% of the said compound. The first layer preferably

consists essentially of the said compound. The said compound may have an effective work function in the device of less than 3.5eV

The said material of which the second layer is comprised preferably has a work function of less than 3.5eV, less than 3.4 eV, or less than 3.3 eV or less than 3.2 eV, or less than 3.2 eV or less than 3.1 eV or less than 3.0 eV. The second first preferably comprises more than 80%, more then 90%, or than 95% or most preferably more than 99% of that material. The second layer preferably consists essentially of that material.

The material of any layer of the cathode that is in contact with the opto-electrically active region preferably does not cause significant degradation of the material of the active region when the two are in contact. The material of any layer of the cathode that is not contact with the opto-electrically active region may be a material that is capable of causing degradation of the material of the active region when the two are in contact. The said compound of the first layer may, when in contact with the material of the active region, form an intermediate state between that of the material of the active region and that of the said material of the second layer.

The third layer suitably comprises a material (a "higher work function material") having a higher work function than those of the first and second cathode layers. The work function of the higher work function material is preferably greater than 3.5 eV or more preferably greater than 4.0 eV. The higher work function material is suitably a metal. The higher work function material and/or the third layer itself preferably has an electrical conductivity greater than  $10^5 \text{ } (\Omega \cdot \text{cm})^{-1}$ . The higher work function material is preferably Al, Cu, Ag, Au or Pt; or an alloy of two or more of those metals; or an alloy of one or more of those metals together with another metal, or an oxide such as tin oxide or indium-tin oxide. The thickness of the third layer is preferably in the range from 1000 Å to 10000 Å, preferably in the range from 2000 Å to 6000 Å, and most preferably around 4000 Å.

The second layer is preferably adjacent to the first layer. The third layer is preferably adjacent to the second layer. Alternatively, the cathode may comprise further layers located between the first, second and/or third layers. The cathode is preferably inorganic, most preferably metallic.

One of the electrodes is preferably light-transmissive, and most preferably transparent. This is preferably but not necessarily the anode electrode, which could be formed of tin oxide (TO), indium-tin oxide (ITO) or gold.

The opto-electrically active region may be light-emissive or (suitably on the application of a suitable electric field across it) or may be light-sensitive (suitably generating an electric field in response to incident light). The opto-electrically active region suitably comprises a light-emissive material or a light-sensitive material. Such a light-emissive material is suitably an organic material and preferably a polymer material. The light-emissive material is preferably a semiconductive and/or conjugated polymer material. Alternatively the light-emissive material could be of other types, for example sublimed small molecule films or inorganic light-emissive material. The or each organic light-emissive material may comprise one or more individual organic materials, suitably polymers, preferably fully or partially conjugated polymers. Example materials include one or more of the following in any combination: poly(p-phenylenevinylene) ("PPV"), poly(2-methoxy-5(2'-ethyl)hexyloxyphenylenevinylene) ("MEH-PPV"), one or more PPV-derivatives (e.g. di-alkoxy or di-alkyl derivatives), polyfluorenes and/or co-polymers incorporating polyfluorene segments, PPVs and related co-polymers, poly(2,7-(9,9-di-n-octylfluorene)-(1,4-phenylene-((4-secbutylphenyl)imino)-1,4-phenylene)) ("TFB"), poly(2,7-(9,9-di-n-octylfluorene) - (1,4-phenylene-((4-methylphenyl)imino)-1,4-phenylene-((4-methylphenyl)imino) - 1,4-phenylene)) ("PFM"), poly(2,7 - (9,9 - di-n-octylfluorene) - (1,4-phenylene-((4-methoxyphenyl)imino)-1,4-phenylene-((4-methoxyphenyl)imino)-1,4-phenylene)) ("PFMO"), poly (2,7-(9,9-di-n-octylfluorene)

("F8") or (2,7-(9,9-di-n-octylfluorene)-3,6-Benzothiadiazole) ("F8BT"). Alternative materials include small molecule materials such as Alq3.

There may be one or more other layers in the device. There may be one or more charge transport layers (preferably of more or more organic materials) between the active region and one or other of the electrodes. The or each charge transport layer may suitably comprise one or more polymers such as polystyrene sulphonic acid doped polyethylene dioxythiophene ("PEDOT-PSS"), poly(2,7-(9,9-di-n-octylfluorene)-(1,4-phenylene-(4-imino(benzoic acid))-1,4-phenylene-(4-imino(benzoic acid))-1,4-phenylene)) ("BFA"), polyaniline and PPV.

According to a second aspect of the present invention there is provided a method for forming an opto-electrical device, the method comprising: depositing an anode electrode; depositing over the anode electrode a region of an opto-electrically active material; depositing over the region of opto-electrically active material a material having a work function below 3.5 eV to form a first cathode layer; and depositing over the first cathode layer another material having a work function below 3.5 eV to form a second cathode layer of a different composition from the first cathode layer.

The present invention will now be described by way of example with reference to the accompanying drawings, in which:

figure 2 is a cross-section of a light-emissive device;

figures 3 to 4 show data on the performance of several light-emissive devices; and

figures 5 and 6 show experimental data for a set of devices having cathodes of different compositions;

figure 7 shows experimental data for a set of devices having cathodes of different configurations; and

figures 8 and 9 show experimental data for devices having cathode layers of different thicknesses.

The illustrated thicknesses of the layers in figure 2 are not to scale.

The device of figure 2 comprises an anode electrode 10 and a cathode electrode 11. Located between the electrode layers is an active layer 12 of light-emissive material. A charge transport layer 13 of PEDOT:PSS is located between the anode electrode 10 and the light-emissive layer 12. The device is formed on a glass substrate 14.

The metallic cathode 11 comprises three layers. Next to the emissive layer 12 is a first layer 15, of calcium. Over that is a second layer 16, of lithium. Over that is a third layer 17, of aluminium. As will be described below, this structure has been found to provide a significant increase in device efficiency.

To form the device of figure 2 a transparent layer of ITO to form the anode electrode 10 may first be deposited on a sheet of glass 14. The glass sheet could be a sheet of sodalime or borosilicate glass of a thickness of, for instance, 1mm. The thickness of the ITO coating is suitably around 100 to 150nm and the ITO suitably has a sheet resistance of between 10 and 30  $\Omega/\square$ . ITO-coated glass substrates of this type are commercially available. As an alternative to glass, the sheet 14 could be formed of perspex. As an alternative to ITO, gold or TO could be used as the anode.

Over the ITO anode is deposited a hole transport or injecting layer 13. The hole transport layer is formed from a solution containing PEDOT:PSS with a ratio of PEDOT to PSS of around 1 to 5.5. The thickness of the hole transport layer is suitably around 500 Å. The hole transport layer is spin-coated from solution and then baked at around 200°C for 1 hour in a nitrogen environment.

Then the electroluminescent layer 15 is deposited. In this example, the electroluminescent layer is formed of 20% TFB in 5BTF8. The term 5BTF8 refers to poly (2,7-(9,9-di-*n*-octylfluorene) ("F8") doped with 5% poly-(2,7-(9,9-di-*n*-octylfluorene)-3,6-benzothiadiazole) ("F8BT"). the term TFB refers to poly(2,7-(9,9-di-*n*-octylfluorene)-(1,4-phenylene-((4-secbutylphenyl)imino)-1,4-phenylene)).



This mixture is coated over the hole transport layer by spin-coating typically to a thickness of around 750 Å. Other materials such as PPV could be used for the emissive layer. The emissive layer could be formed by other routes such as blade or meniscus coating and could be deposited in precursor form if desired.

The cathode is then deposited. The three distinct layers of the cathode are deposited by successive thermal evaporation steps *in vacuo* at a base pressure of less than  $10^{-8}$  mbar. Preferably the vacuum is not broken between the successive steps, to reduce the possibility of contamination of the interfaces between the layers. One alternative to thermal evaporation is sputtering, but this is less preferred for at least the deposition of the layer 15 adjacent to the emissive layer since it may cause damage to the emissive layer 12. In the first thermal evaporation step the layer 15 is deposited. The layer 15 is of calcium and has a thickness of approximately 5 to 25 Å, preferably around 15 Å. In the second thermal evaporation step the layer 16 is deposited. The layer 16 is of lithium and has a thickness of around 100 to 500 Å. In the third thermal evaporation step the layer 17 is deposited. The layer 17 is of aluminium and has a thickness of around 4000 Å.

Finally, contacts are attached to the layers 10 and 17 and, although the aluminium layer 16 may act to some extent as an encapsulant, the device is preferably sealed in epoxy resin for environmental protection.

In use, when a suitable voltage is applied between the anode and the cathode the light-emissive layer is stimulated to emit light. This passes to a viewer through the transparent anode and the glass cover sheet.

The applicant has found that a device of this type has significantly increased efficiency. Figures 3 to 4 show data for the performance of devices of a similar device to that of figure 2 (devices E to H) and two comparative device designs (devices A to D and devices J to P).

The common structures of the devices were as follows:

- Substrate: glass
- Anode: ITO
- Charge transport layer: 1:5.5 PEDOT:PSS; thickness 500 Å
- Emissive layer: 4:1 5BTF8:TFB; thickness 750 Å

The cathodes of the devices were as follows:

Devices A to D:

- calcium layer of thickness 500 Å adjacent to emissive layer; and
- capping layer of aluminium of thickness 4000 Å.

Devices E to H:

- lithium layer of thickness 500 Å adjacent to emissive layer; then
- calcium layer of thickness 1000 Å; and
- capping layer of aluminium of thickness 4000 Å.

Devices J to P:

- lithium layer of thickness 25 Å adjacent to emissive layer; and
- capping layer of aluminium of thickness 4000 Å.

Figure 3 shows the peak measured efficiencies of the devices in  $\text{lm/W}$  and  $\text{Cd/A}$ . Figure 4 shows the drive voltages for the devices at brightnesses of 0.01, 100 and  $1000 \text{ Cd/m}^2$ . Figure 3 shows that the peak efficiency of devices E to H is markedly greater than those of the other devices. Figure 4 shows that devices E to H do not suffer any significant increase in drive voltage, and have significantly lower drive voltages than devices J to P.

Figures 5 to 9 show data for further similar devices. Figure 5 shows experimental data for devices comprising an ITO anode, an 80nm layer of PEDOT:PSS, a 63nm layer of a blue emissive material (spin-coated in a glovebox) and a cathode formed of a first layer next to the emissive layer of a composition as indicated against the respective plot, a second 10nm layer of Ca and a final layer of Al. Figure 6 shows experimental data for devices comprising an ITO anode, an 80nm layer of PEDOT:PSS, a 70nm layer of a green emissive material (F8:TFB:F8BT spin-

coated in a glovebox) and a cathode formed of a first layer next to the emissive layer of a composition as indicated against the respective plot, a second 10nm layer of Ca and a final layer of Al. The experimental data are: electroluminescence spectra, luminous efficiency against voltage, current density against voltage, brightness against voltage and brightness against time. The efficiency data are summarised as follows:

Material of first cathode layer	Blue: maximum Lm/W	Green: maximum Lm/W
MgF <sub>2</sub>	0.30	8.5
MgI <sub>2</sub>	0.01	0.12
LiF	2.0	15
LiCl	0.18	10
LiBr	0.05	12
LiI	0.35	13
CsCl	0.60	0.9
CsBr	0.75	4.5
CsI	0.80	8.0
YF	1.25	14
CaAl	0.73	16

The EL spectra of the blue emitters were only slightly dependant on the cathode materials used, those with higher current densities showing the typical aggregate feature. Green spectra were relatively independent of the cathode materials used. The device performance appeared to be principally dependant on the metal constituent of the first cathode layer. The Mg-based devices had the worst performance for both emissive polymers, with relatively low efficiencies and currents. Cs-based devices had intermediate performance. LiF gave the highest performing devices. Other Li halides had relatively poor performance for blue emission and variable efficiency for green.

Figure 7 shows efficiency data for similar devices having ITO anodes, a PEDOT:PSS layer, an emissive layer capable of emitting blue, green or red light (as indicated on the respective plot) and electrodes of:

- (a) a Ca layer adjacent to the emitter and an upper layer of Al;
- (b) a LiF layer (6nm thick) adjacent to the emitter, then a layer of Ca (10nm thick) and an upper layer of Al;
- (c) a Ca layer (5nm thick) adjacent to the emitter, then a layer of LiF (6nm thick) and an upper layer of Al.

Figure 8 shows efficiency data as a plot of maximum  $Lm/W$  for similar blue, green and red devices having a range of thicknesses for the LiF layer in the Ca/LiF/Al configuration. Figure 9 shows efficiency data as a plot of maximum  $Lm/W$  for devices having a range of thicknesses for the LiF layer in the LiF/Ca/Al configuration.

The applicant has also obtained advantageous results by replacing the Ca layer in such devices with a similar layer of Yb or Ba. Other materials such as Sm, Y and Mg would be expected to yield similar results.

Most of the above devices include in their cathodes a layer of a group 1 or group 2 metal halide, such as LiF. Other group 1 and 2 metal compounds and complexes, such as LiO have been investigated by the applicant and found to give advantageous results. Transition metal halides, compounds and complexes, such as YF (see above) may also give advantageous results. Organic complexes of group 1, group 2 or transition metals may also give advantageous results. These materials include materials that may potentially operate by providing a barrier effect (e.g. LiO) or by another effect due to their low effective work function in this situation (e.g. LiF).

It is believed that, when the layer 15 of the cathode that is adjacent to the emissive layer 12 is sufficiently thin that the properties of the overlying cathode layer 16 can influence charge injection from the cathode into the emissive layer, there is an opportunity to select materials for the layers 15 and 16 such that by a combination

of their properties the performance of the device can be enhanced. Possible mechanisms for this enhancement are believed to include: (a) prevention by the layer 15 of adverse interactions between organic layer(s) of the device (e.g. layer 15) and the material of the layer 16, whilst retaining at least some of the injection properties of the material of the layer 16; and (b) the formation by the layer 15 (e.g. with organic layer(s) such as layer 15) of intermediate states that aid electron injection from the layer 16. The layer 15 should be sufficiently thin to allow the effect to occur but sufficiently thick that it can be deposited reproducibly and uniformly (without excessive defects). To exploit possible mechanism (a) the layer 16 could be formed from a material that is more reactive than that of layer 15, but has a lower work function. It should also be noted that highly advantageous performance is also obtained when a layer of a suitable material (e.g. LiF) is spaced slightly from the emissive material, as in the Ca/LiF/Al devices of figures 7 and 8. In general, possible mechanisms include surface induced dipoles, modified work functions, charge transfer formation of chemically stable compounds and dissociation of the compound layer of the cathode to form a doped injection layer.

It should be noted that in assessing experimentally devices of the types described above the upper layer of the cathode (e.g. of Al) provides important protective effects. Instead of Al other suitable materials include Ag or ITO, which have the advantages of being able to provide a transparent layer whereby the whole cathode may be transparent or at least translucent. This is advantageous for devices that are intended to emit through the cathode.

A device of the type described above may form a pixel of a multi-pixel display device.

The devices described above may be varied in many ways within the scope of the present invention. For example, the capping layer 17 could be omitted; the layers could be formed of different materials; additional layers could be present, in the cathode or elsewhere in the device; or one or more additional charge transport layers could be provided between the light-emissive layer and either or both of the

electrodes to assist charge transport between the respective electrode and the light-emissive layer and/or to resist charge transport in the opposite direction. The emissive material could be of the class of sublimed molecular films, as described for example in "Organic Electroluminescent Diodes", C. W. Tang and S. A. VanSlyke, Appl. Phys. Lett. 51, 913-915 (1987). The locations of the electrodes could be reversed so that the cathode is located at the front of the display (closest to the viewer) and the anode is at the back.

The same principles may be applied to devices for the detection rather than the generation of light. By replacing (if necessary) the light-emissive material with a material that is capable of generating an electrical field in response to light the improved characteristics of the improved electrodes as described above may be used to enhance detection voltages and/or efficiency.

The applicant draws attention to the fact that the present invention may include any inventive feature or combination of features disclosed herein either implicitly or explicitly or any generalisation thereof, without limitation to the scope of any of the present claims. In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention.